Chapter 4

Technical Details

This chapter, together with the appendices, describes the steps of the risk assessment, the data used in the analysis, and the models and methods used to quantify risk and uncertainties.

4.1 Overview of the Risk Assessment Process

The models used in this risk assessment address the spread of tritium releases from the NTLF, contact with human populations, metabolism within the human body, and potential health impacts. The primary goal of these models is to clarify how tritium

- Remains or spreads within the envelope of air to which it is released
- Is transported to another compartment by cross-media transfer that involves dispersion or advection (i.e., volatilization, precipitation, etc.)
- Is physically transformed by radioactive decay

The models' parameters were verified by matching calculated tritium concentrations with the tritium concentrations measured in air and surface runoff in the vicinity of the NTLF and in Berkeley. Using site-specific data and the calibrated parameters, the models determine the tritium concentrations in air, surface water, soils, and plants adjacent to the NTLF. These contamination levels provided the basis for estimating the corresponding doses as well as the risks to people in the three zones.

4.2 Tritium Properties and Sources

A tritium atom has two neutrons, while the common hydrogen (protium) atom has none. Tritium's atomic weight is 3. Deuterium, with one neutron, has an atomic weight of 2, and protium's atomic weight is 1 (see Figure 4-1). Tritium decays to helium through beta decay—the emission of a beta particle from its nucleus:

$$^{3}H \rightarrow {}^{3}He + e^{-} \quad .$$

Tritium's **radioactivity** per unit mass makes it a good tracer and label. A count of nuclear decays per unit time from a known mass or volume allows specific activity (analog of concentration) to be calculated. Because nuclear disintegrations are easily monitored, any molecules that have incorporated tritium are easily differentiated from non-labeled forms. Therefore, tritium has great utility for experiments in which the transport or fate of particular chemicals must be identified. Tritium can be incorporated, via substitution for protium, into any molecule or compound that contains hydrogen.

Tritium represents little or no external dose hazard, because the maximum energy of its beta particles is insufficient for skin penetration. The measured and calculated maximum penetration depth of tritium's beta particles in H_2O is 6 micrometers (µm). Considering that the nonliving outer skin layer (stratum corneum) is 10 to 100 µm thick, the epidermis is 100-200 µm thick, and the dermis is 1000-3000 µm thick, the penetration

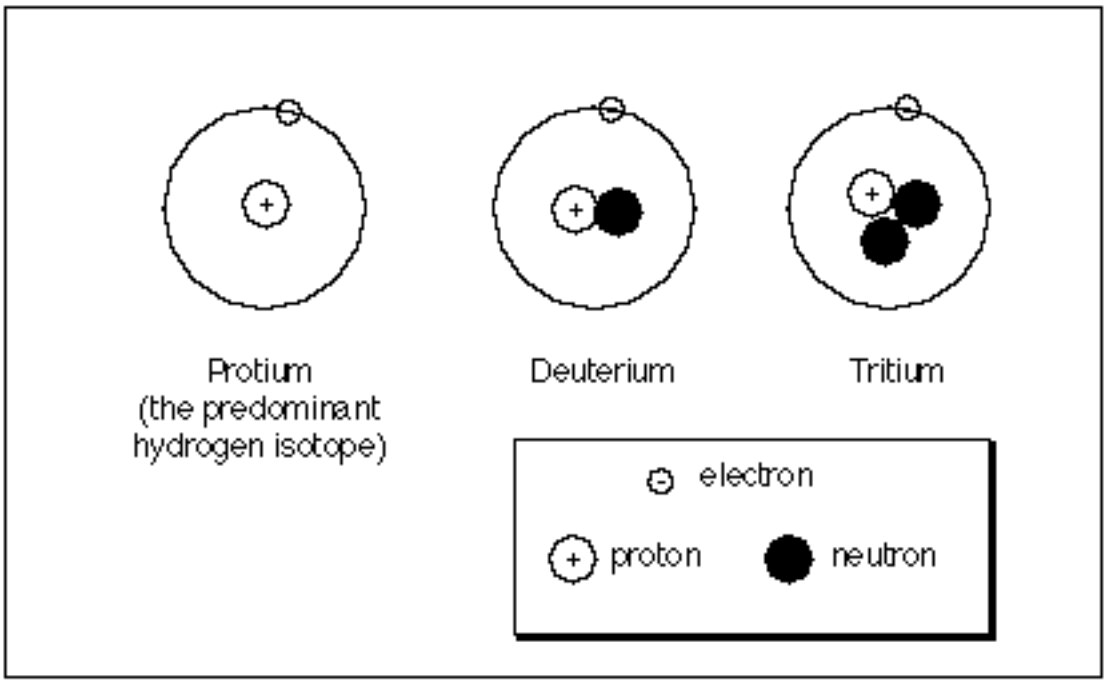


Figure 4-1. The three isotopes of hydrogen and their atomic structures.

of tritium's beta particles through skin is not a big concern. However, once ingested, tritium's minimal penetration depth could be sufficient to inflict deleterious effects.

The radioactive half life of tritium is 12.3 years. The radiological units commonly used to characterize exposure, dose, **dose equivalent** and radiation protection standards for tritium are listed in Table 4-1.

Table 4-1
Common Radiological Units

Unit or quantity	Symbol	Brief description	Comment
Becquerel	Bq	1 nuclear disintegration per second	SI unit of radioactivity
Curie	Ci	3.7×10^{10} nuclear disintegrations per second	Older unit of radioactivity often still used in the US(a)
Roentgen	R	2.58×10^{10} coulombs per kg (photons in air)	Special unit of exposure
Gray	Gy	1 joule/kg	SI unit of radiation dose
Rad	rad	100 erg/g (= 0.01 Gy)	Older unit of radiation dose often still used in the US(a)
Dose equivalent	H	Dose x RBE	Used in radiation protection
Quality factor	RBE	Relative Biological Effectiveness of radiation	Used in radiation protection
Sievert	Sv	Gy x RBE	SI unit of dose equivalent
Rem	rem	rad x RBE	Older unit of dose equivalent often still used in the US(a)

Footnote to Table 4-1:

(a) While all scientific papers employ the SI units, official US regulatory values for dose exposure are given in rems, and the current US unit of radioactivity remains the curie.

4.2.1 Physical and Chemical Properties of Tritium

Tritium is found in the environment in three principal forms—molecular tritium (T_2 or HT), tritiated water (HTO), and organically bound tritium (OBT). Tritiated water is the most abundant chemical form of tritium in the environment. HTO's properties are very similar to those of water. Because the difference in atomic weight is relatively small, the physical properties of HTO and H_2O are more similar than those of tritium and hydrogen. HTO is taken up by organisms and environmental media far more readily than molecular tritium. HTO is the principal form of tritium released from the NTLF.

A small fraction of tritium is incorporated into organic molecules exposed to tritium gas and HTO. This organically bound tritium (OBT) has a different metabolism than HTO. Following exposure to HTO, tritium may be converted to OBT and retained in the body for a longer period [Murphy, 1984]. Table 4-2 gives the physical and chemical characteristics of tritium that are relevant for a dose and risk assessment.

Table 4-2
Physical and Chemical Characteristics of Tritium

Property	Value	Reference
Radioactive half life ($T_{1/2}$)	12.35 y	NCRP [1985]
Decay constant (= 0.693/$T_{1/2}$)	5.6×10^{-2} y^{-1} 1.780×10^{-9} s^{-1}	NCRP [1985]
Average beta decay energy	5.685 keV	NCRP [1985]
Maximum beta decay energy	18.6 keV	NCRP [1985]
Average track length (water)	0.56 µm	Okada and Momoshima [1993]
Maximum track length (water)	6.0 µm	Okada and Momoshima [1993]
Maximum track length (air)	5 mm	Okada and Momoshima [1993]
Radioactivity for 1 g of T_2 (gas)	3.59×10^{14} Bq 9.7×10^{3} Ci	Okada and Momoshima [1993]
1 atom T per 10^{18} atoms H = 0.118 Bq HTO per L (water) = 3.2 pCi HTO per L (water)	1 tritium unit (TU) or 1 tritium ratio (TR)	Okada and Momoshima [1993]

4.2.2 Sources of Tritium Release in the Environment

The major natural source of tritium is cosmic ray reactions in the upper atmosphere. A minor portion of the annual natural tritium production comes from the earth's crust, a result of neutron capture reactions by ^{6}Li in rocks. The steady-state global inventory of tritium from all natural sources is estimated to be in the range of 1 to 1.3×10^{18} Bq [Okada and Momoshima, 1993]. Based on a 12.3 year half-life, this inventory corresponds to an annual production of 0.062×10^{18} Bq/y. Measurements taken before open-air nuclear testing began (before 1950) indicate that HTO in natural waters in the U.S. ranged from 0.14-7.9 Bq/L for Chicago rain water, 0.16-0.21 Bq/L for Lake Michigan water, and 0.30-0.77 Bq/L for the Mississippi [Okada and Momoshima, 1993].

Anthropogenic sources of tritium in recent decades have far exceeded natural sources. Atmospheric nuclear weapons tests in the 1950s and 1960s are estimated to have produced from 185 to 240 $\times 10^{18}$ Bq of tritium [Okada and Momoshima, 1993]. It is estimated that, in the 1990's, the legacy of the nuclear weapons test of the 1950's and 1960's is an additional 52×10^{18} Bq of tritium in the current global inventory [Okada and Momoshima, 1993].

Normal releases of tritium from nuclear facilities are estimated to produce 0.02×10^{18} Bq/y and off-normal releases an additional 0.001×10^{18} Bq/y with a resultant steady-state buildup of 0.4×10^{18} Bq globally [Okada and Momoshima, 1993]. Based on total previous levels of production, the legacy of luminous products (such as watch dials) is estimated to currently release 0.4×10^{18} Bq/y with a resultant steady-state build up of 7.4×10^{18} Bq globally [Okada and Momoshima, 1993]. However, the luminous-dial source is expected to decrease in time.

The combined natural and anthropogenic emissions of tritium result in a current global inventory of approximately 53×10^{18} Bq, which is about 50 times greater than tritium levels due to natural sources alone. However, much of this tritium is deposited in the deep ocean where it is unavailable to the circulating waters of the Earth. Okada and Momoshima [1993] estimate that current levels of tritium in surface, ground and rain water are in the range 0.1 to 8 Bq/L. Based on these concentrations they estimate that current tritium levels in humans are 1.7 Bq/kg and result in an annual dose of 0.05 μGy per year (or 0.09 μSv per year assuming that the relative biological effectiveness (RBE) is on the order of 1.8). The RBE, the estimate of tissue damage of tritium beta emissions relative to gamma rays, is used to convert tissue doses in μGy to gamma-equivalent doses in μSv, and is discussed further in Section 4.6. The United Nations Scientific Committee on the Effects of Atomic Radiation reports a global average dose of 0.01 μGy per year for the human population [UNSCEAR, 1993]. Picking the middle value in this range, 0.03 μGy per year, and again assuming that the RBE of tritium is on the order of 1.8, we find that this is about forty thousand times lower than the average background radiation dose of 2400 μSv reported by UNSCEAR [1993]. The 2400 μSv background value reported by UNSCEAR is attributable to all natural sources of radioactivity—cosmic rays, terrestrial gamma rays, natural radionuclides in the body, and radon and its decay products. Based on the risk factor of 0.04 fatal cancers per Sv recommended by UNSCEAR [1993] for low-dose exposures to working populations, the 2400 μSv total background dose per year corresponds to a population risk of 100 fatal cancers per million people per year and an individual risk of 7 in a thousand per lifetime. In contrast, a 0.03 μGy tritium background dose per year combined with the risk factors derived below (in Section 4.6.4) corresponds to a population risk of 0.003 fatal cancers per million people per year and an individual risk on the order of 2 in ten million per lifetime.

The NTLF currently releases on the order of 3.7×10^{12} Bq/y (100 Ci/y) of tritiated water. This number is typical of annual releases since 1990 and is lower than during the period 1982 to 1990.

4.3 Tritium Releases from the NTLF

The NTLF is designed and operated so that multiple layers of defense restrict the release of tritium to the environment.

Tritium comes to the NTLF facility chemically bound to a uranium bed contained in a sealed metal cylinder. At the NTLF the cylinders are attached to a closed system inside a ventilated glove box. The cylinders are heated to release the chemically-bound tritium from the uranium. All formation reactions take place in the closed system within the glove box.

Two main components of this system are designed to trap or recirculate tritium to prevent its release to the environment:

- The glove-box ventilation system, tritium recovery system, and silica-gel traps, and
- The reaction manifold and the secondary uranium bed.

Tritium can enter the ambient air compartment from the NTLF via three major pathways (see Figure 4-2):

- *Tritium in air drawn through the glove-box ventilation system.* Directed through silica-gel traps, after which booster blowers direct it into the main stack trunk-line. The box-air would be contaminated mainly by fugitive losses through gaskets as well as some diffusional losses through the steel tubing.
- *Tritium in the reaction manifold that fails to sorb out in the secondary U-bed.* Directed through an HTO recovery system. The gaseous residual from this process is then sent through silica-gel traps and onward to a tributary pipe that ultimately joins the main stack trunk-line. This tritium is most likely in the form of HTO.
- *Off-gases passing through the chemistry lab hoods (i.e., laboratory air) as well as any off-gases from the pump-shed* (including pumps, copper oxide furnaces and storage tank). These are directed into the main stack trunk-line.

All postulated releases from the NTLF go to the air compartment as HTO. When tritium is released to the environment—whether into air, water, or soil—it spreads rapidly.

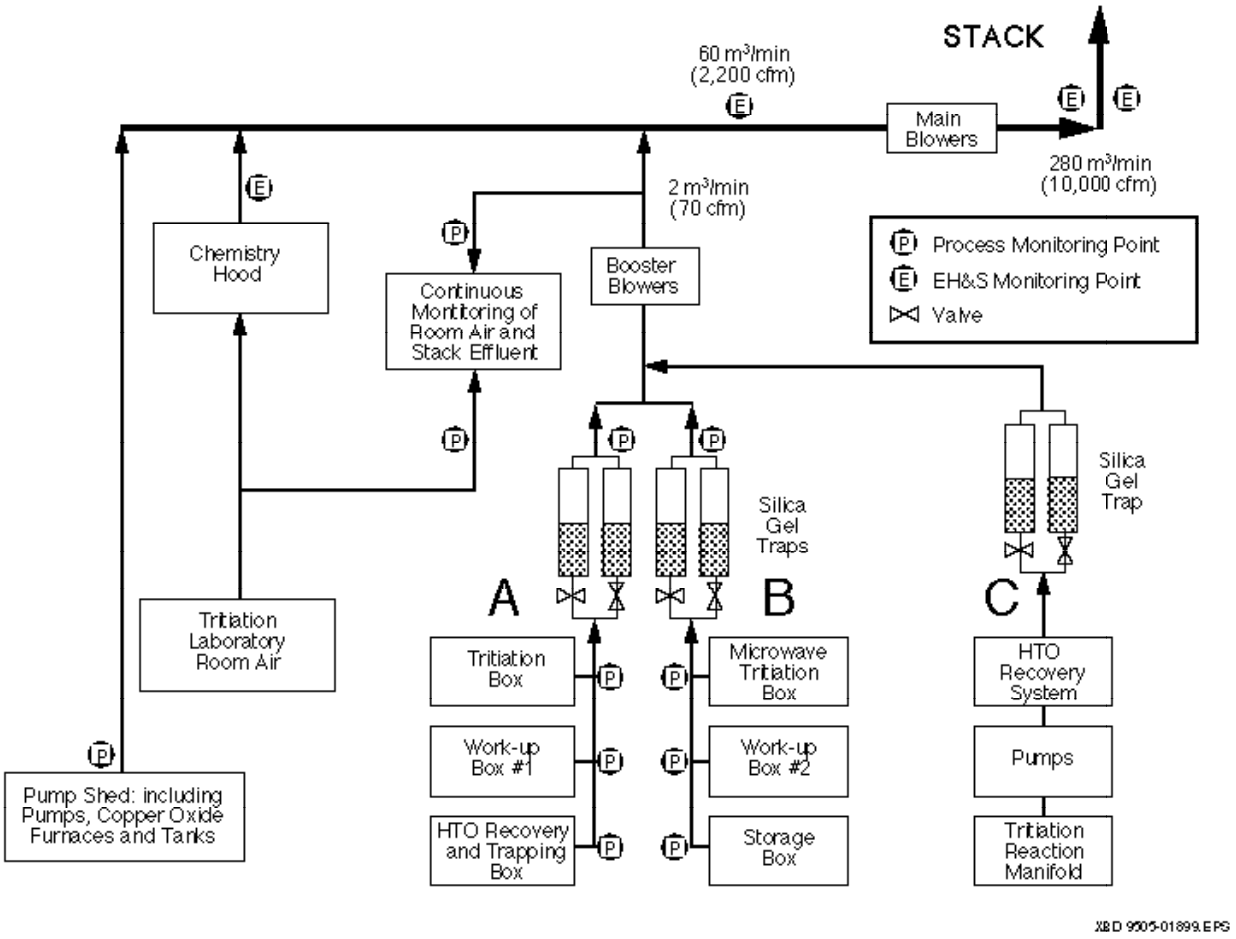


Figure 4-2. NTLF exhaust schematic.

4.4 Environmental Distribution of Tritium Releases from the NTLF

The predominant influences on the relative distribution of HTO in the environment are [Murphy, 1993]:

- The hydrogen cycling processes interacting between the various media (compartments) of the release environment
- The water content of these media

The two influences suggest the importance of understanding the water budget of the release site. The environmental cycling of tritium follows quite closely that of natural hydrogen as it occurs in gas, water, and organic molecules. Perhaps because of hydrogen abundance, no sequestering processes (bioaccumulation) in biota have evolved for hydrogen (or tritium), and thus there is no mechanistic reason to expect biomagnification, which is a metabolically mediated buildup in biological tissues.

However, because hydrogen can bind to organic molecules, we might expect some accumulation as a result of OBT.

A review of the field study literature relating to the fate and transport of HTO in the environment provided some insight into the distribution of HTO subsequent to a continuous atmospheric release, and proved helpful in developing a customized HTO fate and transport model. The sections that follow look at major components of this model. Appendix A contains details of the model structure and the rationale for the model components.

4.4.1 Model Structure

For Zones 1 and 2, we used a two-compartment model to estimate the steady-state distribution of HTO between air and soil as a result of a constant HTO emission to the atmosphere. This is an idealization, constructed to obtain an approximate HTO distribution that is consistent with HTO affinities, site-specific characteristics, and observed environmental parameters (e.g., precipitation, runoff, and infiltration). See Appendix C for an account of site-specific characteristics.

Using the principle of mass conservation for each compartment, the model provides an algorithm for predicting the steady-state HTO concentrations in the soil and air compartments. The overall model structure is illustrated in Figure 4-3. The premises of this modeling approach are as follows:

- HTO will distribute primarily in the aqueous phase of each compartment
- OBT in any compartment can be accounted for by increasing the effective residence time
- Water-phase tritium activities in each compartment will be equal under equilibrium conditions.

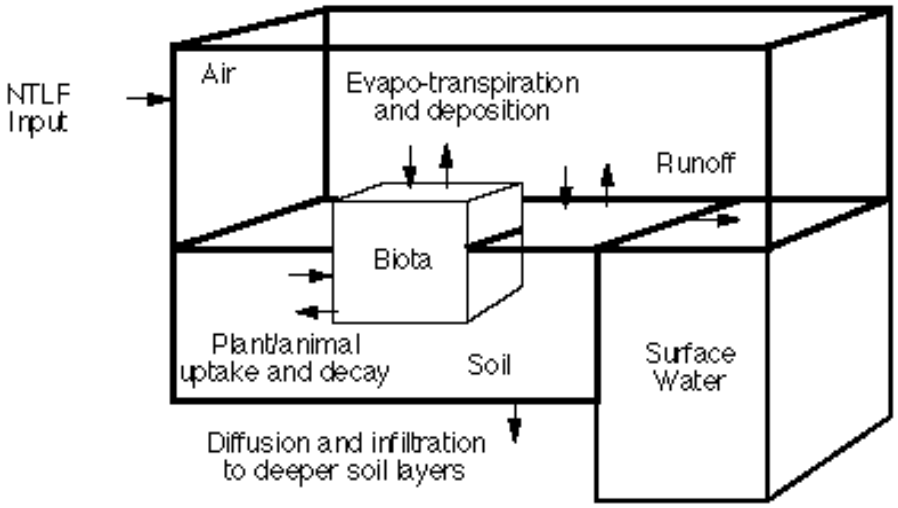


Figure 4-3. Compartment model for assessing the environmental fate of tritiated water emissions from the NTLF.

4.4.1.1 Steady State Mass Balance Equations

The steady-state equations describing gains and losses in the two compartments were solved for the steady-state inventory in each compartment. Table 4-3, gives the gains and losses considered for each compartment. Equations 4-1 and 4-2 express gains and losses for the air and soil compartments, respectively.

$$S + T_{sa} N_s = L_a N_a \qquad \text{(air)} \qquad (4\text{-}1)$$

and

$$T_{as} N_a = L_s N_s \qquad \text{(surface soil)} \qquad (4\text{-}2)$$

In equations 4-1 and 4-2, an N represents a compartment's HTO inventory (note that a compartment's bulk and water phase inventories are equivalent) and the T_{ij} (where i and $j = s$ or a) are transfer rate constants, in units of day^{-1}, representing the fraction per unit time of the inventory in compartment i that is transferred to the inventory in compartment j. Here the total compartment activity in Bq is used to represent inventory (activities in Bq are proportional to molar inventories). The compartment abbreviations are a for air, and s for surface soil. The product of an N term and a T term is the rate of change of inventory in Bq / d. $L_i N_i$ represents all losses from compartment i, in Bq / d. The term S in Equation 4-1 represents the rate of HTO input (i.e., the NTLF's HTO emission rate) into the air compartment, in Bq / d. Transfer rate constants are functions of landscape characteristics and environmental mass transfer rates. Details on the derivation of transfer rate constants are provided in Appendix A.

Table 4-3
Summary of HTO Exchange and Loss Between Air and Soil

Compartment	Gains	Losses
(1) Air (both gas and vapor phases– particulate phase ignored)	• Evapotranspiration from Biota and soil • HTO load carried in with outside air (negligible for occupational volume) • ***NTLF HTO release***	• Precipitation scavenging • Radioactive decay • Loss to "outside" air via advective flushing
(2) Soil	• Diffusion from air (ignored) • Washout (scavenged portion) from precipitation • Loading in runoff entering from outside the 'unit world' (neglected since we calculate added risk)	• Diffusion to air (included in evapotranspiration) • Diffusion to deeper soil (lumped in with advection) • Advection to deeper soil • Loss carried away in runoff • Radioactive decay

4.4.1.2 Calculating L_a

For the air compartment, L_a is the sum of all loss-rate constants from the air compartment.

$$L_a = T_{as} + T_{ao} + \lambda \ , \tag{4-3}$$

where T_{as}, in day^{-1} units, is the rate constant for advection and diffusion losses to soil and accounts for rain-water washout from air to ground-surface soil, T_{ao} is the rate constant, in day^{-1} units, for convective dispersion losses in air and λ, in day^{-1} units, is the rate constant for losses due to radioactive decay.

4.4.1.3 Calculating L_s

The soil compartment represents the surface layer of soil, where losses include diffusion to air, diffusion and infiltration to deeper soil layers, runoff to surface water, and radioactive decay. The mass balance that defines the inventory, N_s, in Bq of HTO, is described by Equation 4-2. L_s is the sum of all loss-rate constants from the soil compartment.

$$L_s = T_{sa} + T_{recharge} + T_{runoff} + \lambda \ , \tag{4-4}$$

where T_{sa} is the soil-to-air transfer rate (primarily representing evapotranspiration processes), and $T_{recharge}$ and T_{runoff} are the rate constants for recharge losses to ground water and runoff losses to outside of the landscape unit, respectively. All the rate constants are in day^{-1} units. These loss-rate constants are derived in Appendix A.

4.4.2 Solutions for the Tritium Inventories

By solving Equations 4-1 and 4-2 simultaneously we obtain:

$$N_s = \frac{S}{\frac{L_s L_a}{T_{as}} - T_{sa}} \tag{4-5}$$

$$N_a = \frac{S}{L_a - T_{sa}\frac{T_{as}}{L_s}} \tag{4-6}$$

These solutions are used later to estimate tritium risk to human health. The rate constants used in the equations were selected to ensure that the model reproduces the available measured concentrations of tritium in the air and water from the NTLF site.

4.4.3 Air Dispersion Model for Zone 3

For Zone 3 we used the CAP88-PC microcomputer radionuclide dispersion and dose-assessment code supplied and approved by US/EPA. This model is able to calculate doses and risks to individuals at various distances from the tritium source. For the point of maximum off-site exposure, the dose represents the cumulative exposure from all significant exposure pathways (inhalation, ingestion, air immersion, and surface exposure). The methods and parameters used to calculate the dose are very conservative. In this risk assessment, however, we only use the tritium concentration in air calculated by CAP88 as input data in our model for risk calculations.

4.5 Human Contact with Tritium Releases

For releases of tritium from the NTLF, pathways leading to internal exposures of tritium include:

- HTO vapor entering the body through respiration
- Tritium in water, breast milk, or foods ingested and absorbed through the gastro-intestinal tract
- HTO vapor in air taken up through the skin
- HTO in water taken up through the skin during dermal contact with the contaminated water; e.g., while swimming and wading.

4.5.1 Intake and Uptake

When environmental concentrations of tritium are constant over an exposure duration, ED, the population-averaged intake (for ingestion or inhalation routes) or uptake (for dermal contact) is the average daily exposure rate (AED_{ijk}), in Bq/kg-d, and is given by

$$AED_{ijk} = \left[\frac{C_i}{C_k}\right] \times \left[\frac{IU_{ij}}{BW}\right] \times \frac{EF \times ED}{AT} \times C_k \quad . \tag{4-7}$$

In this expression $[C_i/C_k]$ is the intermedia transfer ratio, which expresses the ratio of tritium concentration in the *exposure* medium (i.e., personal air, tap water, milk, soil, etc.) to the tritium concentration in an environmental medium k (ambient air, soil, surface water, groundwater, etc.). For inhalation and dermal uptake of tritium from ambient air when the environmental and exposure medium are the same, the ratio $[C_i/C_k]$ is unity; similarly, for ingestion and dermal uptake from water, the ratio $[C_i/C_k]$ is also unity; but for ingestion uptake of vegetation, where the environmental medium is air and the exposure medium is vegetation, the ratio $[C_i/C_k]$ is equivalent to the plant/air concentration ratio.

[IU_{ij}/BW] is the intake or uptake factor per unit body weight associated with the exposure medium *i* and route *j*. For exposure through inhalation or ingestion, [IU_{ij}/BW] is the daily intake rate for the exposure medium per unit body weight ; for example, m^3(air) / kg-d, L(milk) / kg-d, or kg(soil) / kg-d. For uptake through the dermal route, [IU_{ij}/BW] is the uptake factor per unit body weight and per unit initial concentration in the applied medium, [L(water) / kg-d or m^3(air) / kg-d]. To illustrate this further, we note that the uptake factor, [IU_{ij}/BW], for dermal contact with water is obtained by multiplying the effective tritium permeability from water, L / m^2 / d, by the exposed skin surface area, m^2, divided by body weight of the exposed individual and that for dermal contact with air, [IU_{ij}/BW] is obtained by multiplying the effective tritium permeability from air, m^3/ m^2 / d, by the exposed skin surface area, m^2, divided by body weight of the exposed individual. Specific development of these factors [IU_{ij}/BW] is described below in Section 4.5.2.4 and explicitly represented in Equations 4-8 and 4-9.

EF is the exposure frequency for the exposed individual, in days per year. *ED* is the exposure duration for the exposed population, in years. *AT* is the averaging time for the exposed population, in days; and C_k is the tritium concentration in environmental medium *k*.

4.5.2 Exposure Factors

In constructing dose models one needs to define the characteristics of individuals in various age / sex categories and the characteristics of the microenvironments in which they live or from which they obtain air, water and food. This section defines the types of anatomical and activity data needed to carry out the **dose assessment** and provides representative values for these parameters. Appendix B describes how these data were obtained and evaluated. An arithmetic mean value and a coefficient of variation (CV)—the arithmetic standard deviation divided by the arithmetic mean—are defined for all exposure factors used in this assessment.

4.5.2.1 Exposure Duration and Averaging Time

In the basic exposure model, the exposure duration (ED) is the amount of time, in years, that the exposed population is assumed to be in contact with a specified environmental contaminant. The averaging time (AT) is the period, in days, over which exposure is averaged. The estimates of risk given in section 4.7 are based on population exposures and the committed dose in a defined population on an annual basis. Thus, for this risk assessment ED and AT represent the same period of time and the ratio *ED* / *AT* in Equation 4-7 is [1 y] / [365 d].

4.5.2.2 Anatomical Properties, Inhalation, and Ingestion

The arithmetic-mean and CV of body weight and body surface area for three age groups—infant, child, and adult is given in Appendix B. The body weight for infants is needed for estimating exposures to tritium in breast milk. Appendix B also contains an evaluation of available data on population breathing rates, ingestion of water during recreational activities, ingestion of breast-milk by infants, and ingestion of home-grown fruits, vegetables and grains. The descriptions, parameter symbols, and values prepared for these inputs are summarized in Table 4-4.

Table 4-4
Values of Human Anatomical and Intake Properties
Used in the Exposure Calculations.[a]

Parameter, symbol	Child[b]		Adult[b]		Combined[b]		Units
Body weight of infants age 0 to 1 y, BW	7.2	(0.3)	--	--	--	--	kg
Body weight, BW	29	(0.24)	71	(0.2)	62	(0.2)	kg
Surface area, SA_b	0.032	(0.09)	0.024	(0.06)	0.026	(0.07)	m^2/kg
Working breathing rate, BR_w	--	--	0.030	(0.3)	--	--	$m^3/kg\text{-}h$
Active breathing rate, BR_a	0.023	(0.3)	0.018	(0.3)	0.019	(0.3)	$m^3/kg\text{-}h$
Resting breathing rate, BR_r	0.008	(0.3)	0.006	(0.2)	0.0064	(0.2)	$m^3/kg\text{-}h$
Breast milk intake, I_{bm} [c]	0.11	(1)	--		--		kg/kg-d
Water intake during recreation, I_{flr}	0.0007	(1)	0.0007	(1)	0.0007	(1)	L/kg-h
Ingestion of homegrown exposed produce, I_{ep}	0.0016	(0.7)	0.00078	(0.7)	0.00096	(0.7)	kg/kg-d
Ingestion of homegrown unexposed produce, I_{up}	0.00095	(0.7)	0.00053	(0.7)	0.00062	(0.7)	kg/kg-d

Footnotes to Table 4-4:

(a) Listed are the arithmetic-mean value and (in parentheses) the estimated CV. Body weights are from Najjar and Roland [1987], breathing rates are from ICRP [1975], tap water intakes are from Yang and Nelson [1986] and Ershow and Cantor [1989], and food intakes are from Yang and Nelson [1986].

(b) The child category covers ages 0 to 15, the adult category covers ages 16 to 70, the combined category is used to represent lifetime equivalent exposure and is obtained by multiplying the child category by 15/70, the adult category by 55/70, and then summing these products.

(c) Breast milk intakes are from Butte et al. [1984] and Whitehead and Paul [1981].

4.5.2.3 Activity Patterns and Exposure Times

Activity patterns define the frequency and duration that could expose individuals to tritium-contaminated media—air, water, soil. For occupational exposures the exposure time per day is typically 8 to 10 hours and the exposure frequency (EF) is 200 to 300 days per year (assuming 50 working weeks per year and from 4 to 6 working days per week). For non-occupational exposures, the U.S. EPA [1989a] reports the average time spent at home indoors as 8 to 16 h / d and the time spent at home outdoors as 0.3 h / d, with an estimated CV in both cases of 0.14.

For estimating possible doses from water recreation activities in creeks running down from the Berkeley Hills, we assume every adult in Zone 3 wades 2 hours per day for 30 days annually (the U.S. EPA [1992a] reports that for recreational swimming, the time spent swimming ranges from 0.5 h / d to 1 h / d and the frequency ranges from 5 d / y to 150 d / y, see Table 4-5).

Table 4-5
Values and Units of Exposure Parameters Used to Characterize Activity Patterns.

Activity pattern	Value used	Likely range	Units	Reference
Exposure time at work, ET_W	9	8 to 10	h/day	This report
Exposure frequency at work, EF_W	250	200 to 300	day/y	This report
Exposure time, at home indoors, ET_h	12	8 to 16	h/day	U.S. EPA [1989a]
Exposure time, at home outdoors, ET_o	0.3	0.02 to 0.4	h/day	U.S. EPA [1989a]
Exposure frequency at home, EF_h	365	n/a	day/y	This report
Exposure time in surface water, ET_{sw}	2	0.5 to 1	h/d	U.S. EPA [1992a]
Exposure frequency to surface water, EF_{sw}	30	5 to 150	day/y	U.S. EPA [1992a]

4.5.2.4 Dermal Uptake from Air

For individuals who are at rest during the time of exposure, the amount of tritium entering the body by **dermal uptake** is approximately equal to that by inhalation [Hill and Johnson, 1993, Pinsom and Langham, 1980]. For an individual at rest, the ratio of inhalation intake per unit body weight (Bq / kg-h) to air concentration (Bq / m^3) is 0.0064 m^3 / kg-h, as defined in Table 4-4. For dermal uptake of tritium from air, the ratio of dermal uptake to air concentration is equal to the product of the effective skin permeability (m / h) and the mass-specific surface area of the body:

$$\frac{inhalation\ intake\ rate}{C_{air}} = 0.0064 m^3 / kg - h \quad (4\text{-}8)$$

$$\frac{dermal\ uptake\ rate}{C_{air}} = K_p^{air}(m/h) \times SA_b(m^2/kg) \quad (4\text{-}9)$$

where K_p^{air} is the effective permeability of tritium in air through human skin and SA_b is the ratio of body surface area to body weight as given in Table 4-4. By equating (4-8) and (4-9) we found that K_p^{air} is on the order of 0.25 m/h, which is somewhat high but not inconsistent with permeabilities that have been measured for organic vapors (EPA, 1992).

4.5.2.5 Dermal Uptake from Water

Dermal uptake of tritium from water pertains to recreational scenarios, such as wading and swimming in creeks. As with air, the dermal uptake of tritium from water is based on the measured ratio of uptake to concentration. The permeability of water on skin has been measured at 1.5×10^{-5} m/h (EPA, 1992). Since the diffusion coefficients of HTO in air and water are essentially the same as H_2O [NCRP, 1985], this value is assumed to be appropriate for HTO.

4.6 The Relation Between Tritium Exposure, Radiological Dose and Health Effects

This section looks at how exposures to tritium are linked to potential health impacts within the exposed population. First, a review of the potential health effects associated with tritium establishes the relation between tissue concentration and radiological dose. To establish the appropriate relation between exposure and dose, we next look at metabolism and dosimetry, followed by regulatory standards that have been established to limit exposure and dose. A derivation of the risk factors used to estimate the incidence of health impacts within the exposed population concludes the section.

4.6.1 Health Risks Associated with Tritium

To quantify the likely magnitude of health risks associated with exposures to tritium, it is necessary to address tritium metabolism and dose in terms of radiation biology and radiation protection methods.

Each decay of a tritium atom releases energy that is carried by the resulting beta particle. The rate of decay is expressed as the product of the number of atoms N and the decay constant, which is equal to 0.693 divided by the half-life, $T_{1/2}$,

$$\textit{decays per unit time} = N \times 0.693 / T_{1/2} \ . \qquad (4\text{-}10)$$

The energy release rate by these decays is equal to the rate of decay times the average beta decay energy E_β (in joule / decay). Furthermore, the energy absorption rate is equal to the energy release rate divided by the tissue mass, M_t.

$$\textit{energy absorption rate} = \frac{E_\beta \times N \times 0.693}{T_{1/2} \times M_t} \ . \qquad (4\text{-}11)$$

The unit for energy absorption in living tissues is the **gray** (Gy). One Gy represents one joule of energy deposited per kilogram (kg) of tissue.

Because few studies are available on tritium-induced health injury in humans, health-risk estimates for tritium must be based on the large number of experiments with animals and cell cultures [Straume, 1993]. These experiments show that exposure to tritiated water results in mutations and cell disruptions that can lead to cancer, heritable genetic defects, and reproductive and developmental effects [Straume, 1993]. These effects are qualitatively similar to the injuries caused by low linear-energy-transfer (LET) radiations produced by cesium-137 and cobalt-60, such as x-rays and gamma-rays, for which a significant amount of human data is available. The quantitative difference between tritium beta emissions and a standard low-LET radiation is expressed by the **relative biological effectiveness (RBE)**. The RBE for tritium ranges from 1 to 3 [Straume, 1993]. This means that although the health effects of the beta doses from tritium are believed to be qualitatively similar to health effects of gamma rays, the beta rays are believed to be more potent per unit energy deposition than gamma rays. However, there have been no human experiments that demonstrate the validity of these conclusions for the weak beta energy of tritium decay. As has been noted by UNSCEAR [1993] there is some likelihood that no health effects would occur at low doses and low dose rates.

4.6.2 Tritium Metabolism and Dosimetry

There is general consensus that the current understanding of the metabolism of HTO is sufficient for radiation protection purposes [Hill and Johnson, 1993]. When it enters the body, HTO quickly reaches equilibrium with hydrogen in the body and imparts a uniform dose to all soft tissues. The ICRP [1978] recommends the assumption that internalized HTO is completely absorbed and mixed rapidly with total body water so that the concentration in all body waters—blood, urine, sweat, sputum, insensible perspiration, and exhaled water vapor—is the same. However, following HTO exposures, a small fraction of tritium will eventually be incorporated into organic molecules as OBT and will have a different metabolic rate than total body water tritium. Because there is no preferential distribution of OBT to any specific body tissue, it can be assumed that both HTO and OBT are uniformly distributed throughout the body, once taken in through some exposure route.

Human studies indicate that, generally, tritium retention can be characterized by a three-component exponential function. These three components have biological half-lives of 6 to 12 days, 10 to 34 days, and 130 to 550 days, with respective median values of 9, 22, and 340 days [Hill and Johnson, 1993]. The first biological half-life is for the body water metabolism of hydrogen and reflects the turnover of water within the pool of body water. The second half-life appears to be related to tritium involved in carbon-tritium bonds, and the last is for tritium incorporated into organic molecules having very slow turnover rates [Hill and Johnson, 1993].

Tritium can also enter the body as OBT through food products. The fate of OBT after ingestion depends primarily on the human body's hydrogen metabolism. Usually, direct uptake and metabolism of OBT has been ignored in models of tritium dosimetry. However, recent reports based on more advanced environmental tritium models indicate that ingestion doses from OBT in food could be higher than doses from equivalent quantities of tritium ingested or inhaled as HTO [Etnier et al., 1984]. To properly assess combined exposures to HTO and OBT, we describe the retention of tritium following exposure with a model that accounts for intake of both. Following the recommendation of Hill and Johnson [1993], we use the four-compartment model proposed by Etnier et al. [1984] to describe tritium retention. One compartment is used to represent the retention of tritium in body water and the other three compartments are used to represent the retention of tritium in different types of organic molecules. This model is illustrated in Figure 4-4.

The λ parameters in this model represent rate constants for the transfer of tritium among compartments. These parameters are measured by studying the retention and loss of tritium in human and animal subjects. Some of these parameters can be determined directly from curves of tritium retention in the body. For example, in Figure 4-4, λ_{wo} is equal to $0.693 / T^{w}_{1/2}$, λ_{lw} is equal to $0.693 / T^{l}_{1/2}$, and λ_{nf} is equal to $0.693 / T^{n}_{1/2}$; where $T^{w}_{1/2}$, $T^{l}_{1/2}$, and $T^{n}_{1/2}$ are the biological half-lives that reflect, respectively, the turnover of hydrogen within the pool of body water, labile tritium involved in non-water bonds, and tritium incorporated into organic molecules that have very slow turnover rates. Other λ parameters are derived from steady-state distributions of tritium activity. Etnier et al. [1984] report the following values (with units of day^{-1}): λ_{wl} is equal to 0.0005463, λ_{wf} is equal to 0.00416, λ_{fw} is equal to 1.5472, and λ_{fn} is equal to 0.10328.

Under steady-state conditions, these parameters can be used to assess the body burden associated with a continuous input of tritium as HTO or OBT by estimating the effective tritium half life, $T^{tlt}_{1/2}$, for a given intake. When HTO is ingested, based on the ranges of compartment half-lives discussed above, the model in Figure 4-4 gives an estimated mean value of $T^{tlt}_{1/2}$ equal to 15 days with a CV of 0.2. When OBT is ingested into either the labile or fast fat compartment, the model in Figure 4-4 gives an estimated mean

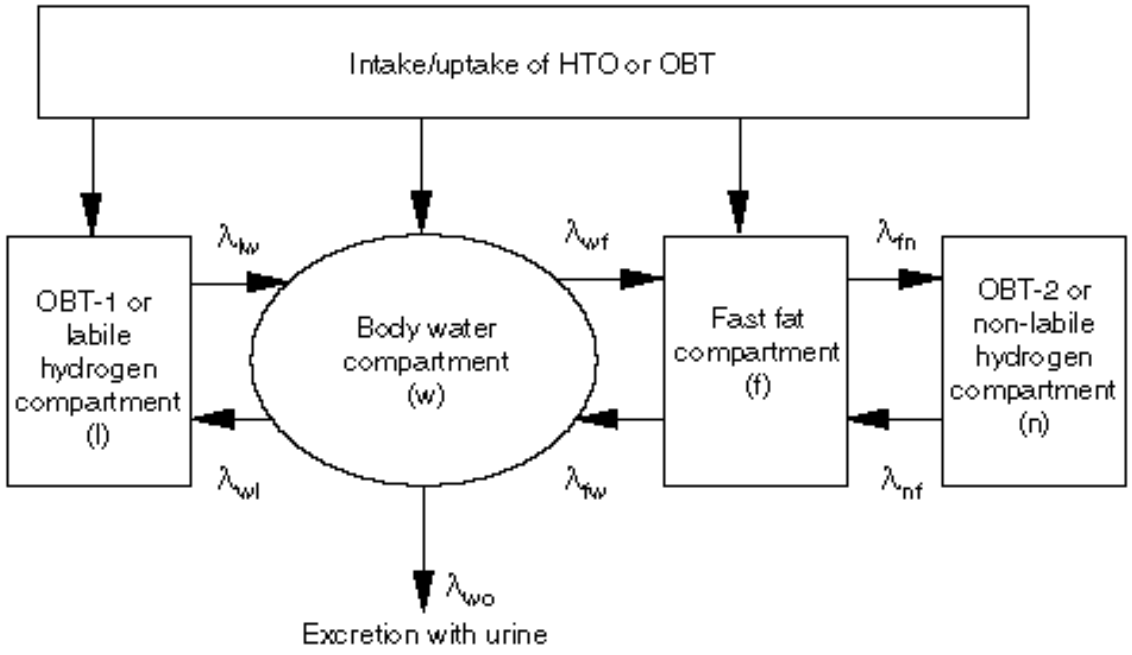


Figure 4-4. Four-compartment model for tritium metabolism, applied to the intake or uptake of HTO and OBT. The four compartments are body water (w); rapid-turnover OBT, which contains labile tritium (l); fast-fat, with rapid turnover of non-labile OBT (f); and slow-turnover, with slow turnover of non-labile OBT (n). The λ parameters are rate constants for tritium transfer among compartments and relate to the half-lives in these compartments.

value of $T_{1/2}^{tlt}$ equal to 48 days with a CV of 0.3. Based on the appropriate effective half-life $T_{1/2}^{tlt}$, the total amount of tritium retained in the body, Q_{total} in Bq, is calculated from

$$Q_{total}(Bq) = \frac{IU \times T_{1/2}^{tlt}}{0.693} \quad . \tag{4-12}$$

From this steady state inventory and the body weight, BW (in kg), we calculate the total body burden (in Bq / kg) and the corresponding dose rate in Gy per year as

$$burden\ (Bq\ /\ kg) = \frac{IU \times T_{1/2}^{tlt}}{0.693 \times BW} \quad , \tag{4-13}$$

$$dose\ rate\ (Gy\ /\ y) = burden \times 5.685 \frac{keV}{dist} \times 3.15 \times 10^{7} \frac{\sec}{year}$$

$$\times 1.6 \times 10^{-16} \frac{Joule}{keV} \qquad (4\text{-}14)$$

$$= burden \times 2.865 \times 10^{-8} \ ,$$

where *dist* means disintegration.

4.6.3 Regulatory Guidance Relevant to Tritium

International, federal, and state agencies have all set standards for controlling human exposures to tritium in both occupational and nonoccupational settings.

For radiation protection in occupational settings, the ICRP [1978] has recommended the use of both an annual limit on intake (ALI) and a derived air concentration (DAC) for HTO. The DAC is the air concentration that would result in the ALI through inhalation and dermal routes for exposure times and exposure frequencies typical in the work environment (2000 hours of exposure per year and 3750 m^3 of air as a annual breathing volume). The 1978 recommendation of the ICRP is that the ALI for HTO be 3 billion Bq (0.08 Ci) and that the corresponding DAC be 800,000 Bq/m^3 (22 $\mu Ci/m^3$). This number corresponds to a committed annual effective dose of 0.05 Sv (5 rem) to workers. Based on the risk factor of 0.04 fatal cancers per Sv recommended for low-dose exposures to working populations by the United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR, 1993], 0.05 Sv corresponds to an annual fatal cancer risk of 0.002 for the working population exposed to this level. Recently, the ICRP [1991] has recommended the reduction of the committed annual effective dose limit for workers from 0.05 Sv to 0.02 Sv. With this recommendation, the ALI and DAC for HTO become 1 billion Bq and 300,000 Bq/m^3, respectively. These new values correspond to a fatal cancer risk of 0.0008 per year of exposure at the 0.02 Sv limit.

Currently, the Code of Federal Regulations (CFR) of the United States (10 CFR-835, 1994) follows the 1978 ICRP guidelines and specifies that exposure at U.S. Department of Energy (DOE) facilities not exceed a committed annual effective dose of 0.05 Sv to workers. Based on this standard, the CFR recommends the same ALI and DAC for tritium as those recommended by the ICRP in 1978. In addition, the CFR specifies that the dose limit for worker during pregnancy is 0.005 Sv (0.5 rem), that any minor exposed to radiation or radioactive material during direct on-site access at a DOE site or facility shall not receive in excess of 0.001 Sv (0.1 rem) total effective dose equivalent annually, and that any member of the public exposed to radiation or radioactive material during direct on-site access at a DOE site or facility shall not receive in excess of 0.001 Sv (0.1 rem), annually. To guarantee compliance with these latter guidelines, a limit of roughly 16,000 Bq/m^3 for HTO-in-air concentrations is required. 10 CFR 20 limits annual worker exposure to 0.05 Sv from both internal and external sources and limits annual public exposure to 0.001 Sv from all exposure routes.

The CFR also specifies maximum contaminant levels in air (40 CFR-61, 1993) and water (40 CFR-141, 1994) for beta particles released from man-made radionuclides to unrestricted areas. For emissions to air, the CFR specifies that emissions of radionuclides to the ambient air from Department of Energy facilities should not exceed those amounts that would cause any member of the public to receive in any year an effective dose equivalent of 0.0001 Sv (0.01 rem). Based on scaling the DAC for working environments from a risk of 0.05 to 0.0001 Sv and adjusting for an annual exposure time of 8,760 h (i.e., 24 h / d for 365 d / y) versus 2,000, we estimate that the ambient concentration limit corresponding to continuous exposure for a member of the public is on the order of 365 Bq / m^3 (10,000 pCi / m^3). The maximum contaminant levels for tritium in water is specified in the CFR as 740 Bq / L (20,000 pCi / L). The State of California uses federal standards for tritium concentration limits in air and water [California Environmental Regulations Section 64443. Man-Made Radioactivity, 1993].

4.6.4 Risk Factors: The Relation Between Radiological Dose and Health Effects

Detrimental effects of toxic chemicals on humans, animals, and plants can be classified as stochastic or nonstochastic effects [ICRP, 1977]. Stochastic effects are those for which the probability of an effect occurring, rather than the severity of effect, is proportional to dose without threshold. Nonstochastic effects are those for which the severity of effect is a function of dose and for which a threshold may exist. For example, the human health effects of carcinogens and many types of genetic effects are assumed to be stochastic. In contrast, the effects of neurotoxins, such as lead and mercury, are assumed to be nonstochastic. The detrimental effects of body burdens of tritiated water are stochastic. This section identifies risk factors that can be used to estimate the likely occurrence of these effects in exposed populations.

Together with previous studies, a large number of radiobiological studies conducted over the past decade indicate that tritium in body water produces the same portfolio of radiogenic effects as that observed following whole-body exposure to penetrating ionizing radiations such as x-rays and gamma rays [Straume and Carsten, 1993], including cancer, heritable genetic defects, and reproductive and developmental effects. Nevertheless, it has been observed and reported that the beta rays produced by tritium have greater biological effectiveness (i.e., damage potential) than x-rays or gamma rays of the same energy [Straume and Carsten, 1993].

We have shown that an annual dose equivalent from tritium exposure can be calculated from tritium concentration in body water by converting this body-water concentration to an estimate of equivalent whole-body energy deposition in Gy. Based on the average dose in Gy for a population, we derive the risk factors to predict the potential incidence of detrimental effects. However, studies showing deleterious effects from tritium uptake were in the million-Bq-per-liter range. These ranges may not be applicable to the concentrations around the LBNL tritium facility.

4.6.4.1 The Risk Factor for Cancer, R_{HTO}^{can}

Exposures to tritiated water appear to induce DNA changes, indicating that HTO might be an initiator of cancer. In addition, there is evidence that HTO can cause **transformations** in mutant stem cells and thus enhance later stages of the progression from normal to cancer cells, thus indicating that HTO might also be considered a promoter of cancer. Types of cancers associated with HTO dose include leukemia and nonleukemia (primarily soft-tissue carcinomas) [Straume, 1993].

Straume [1993] has developed a stochastic dose-response model of fatal cancer risk for HTO doses that is based on the dose-response data for human cancer and a modification for the biological effectiveness of HTO relative to gamma rays. This model expresses the probability of cancer per Gy of dose and is illustrated in Figure 4-5. In this model the risk factor for cancer incidence within a population has respective median and mean values of 0.080 and 0.089 fatal cancers per Gy of dose. According to Straume [1993], the full range of this distribution is from 0.018 to 0.580, and the CV is approximately 1.3. The International Commission on Radiological Protection [ICRP, 1990] recommends a risk factor of 0.05 per Sv for fatal cancers in populations that include adults (of all ages) and children. Thus, the risk factor of 0.089 per Gy used here has an implicit relative biological effectiveness (RBE) of 1.8. However, Straume's [1993] data for RBE used to construct his risk factor suggests that the RBE he used was actually 2.3. This discrepancy suggests that Straume's model differs somewhat from the ICRP [1990] approach.

The factor 0.089 is the risk factor for fatal cancer. In order to determine the total number or incidence of cancers, we multiply the number of fatal cancers by 1.2. This ratio is used by the ICRP in their stochastic dose-response model. This ratio implies that for every 5 fatal cancers predicted to result from radiation exposure, there will be on average a likelihood of 1 nonfatal cancer in addition to five fatal cancers.

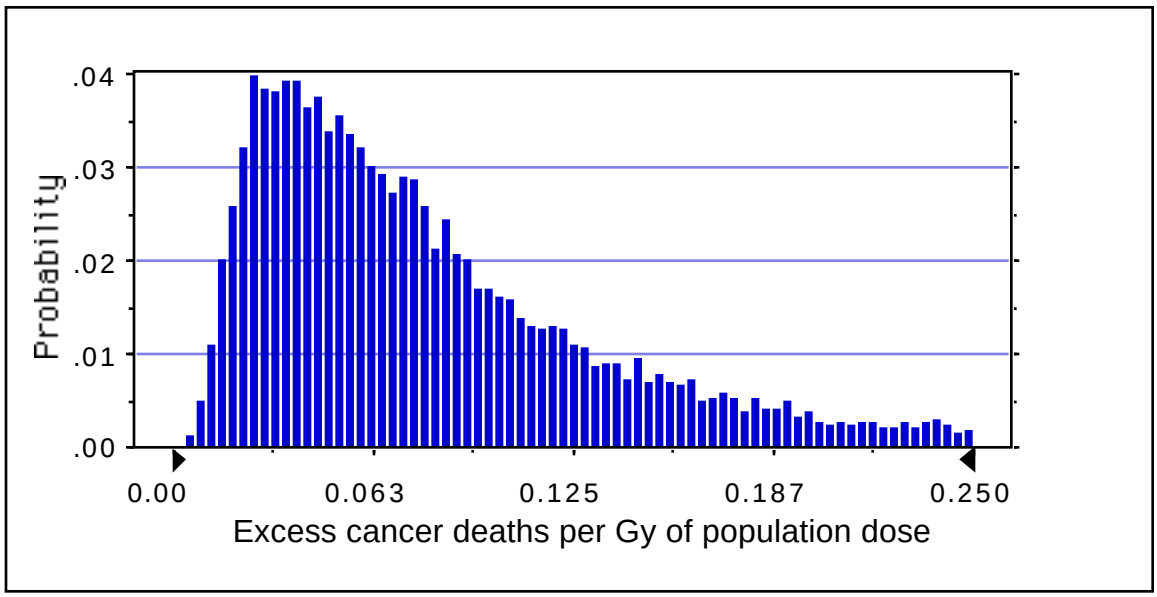


Figure 4-5. The stochastic cancer risk factor for population doses of tritiated water as derived from the model of Straume [1993].

4.6.4.2 The Risk Factor for Heritable Genetic Effects, R_{HTO}^{gen}

To estimate genetic risk to humans from low-level HTO exposures, we use a model developed by Straume [1993], who has used ranges and distributions of gamma-ray-induced risks to construct a stochastic-dose response function for the number of heritable genetic defects expected per Gy of population dose. The distribution of defects per unit dose obtained from this model is shown in Figure 4-6. This distribution has respective median and mean values of 0.006 and 0.0066 defects per live-born Gy of population dose in the first generation. The range of this distribution is from 0.0014 to 0.033, and the CV is approximately 1.3.

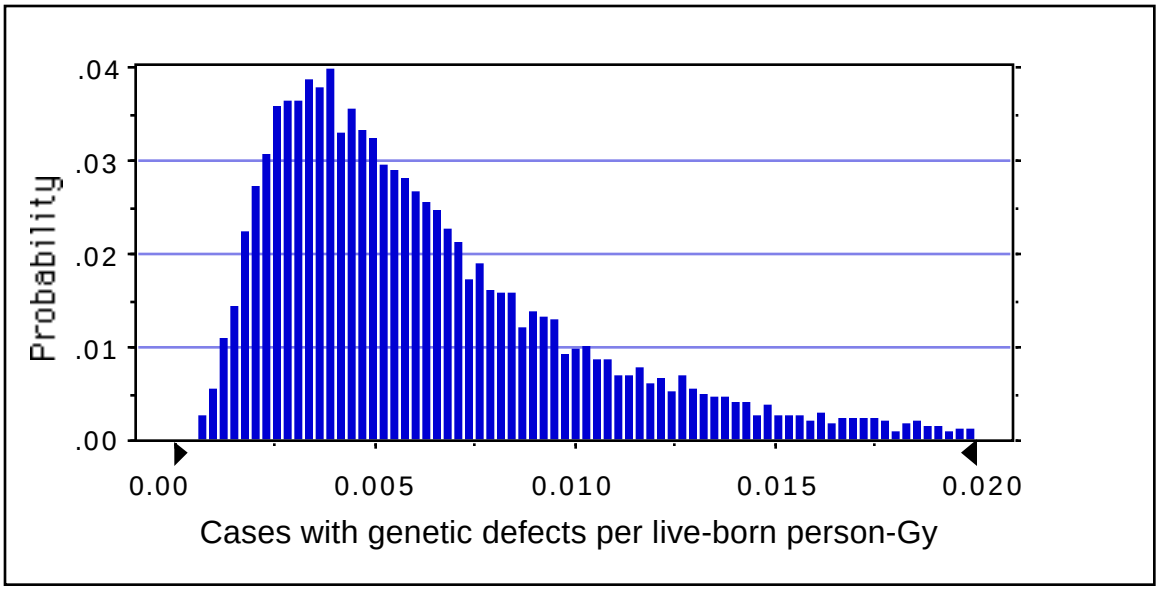


Figure 4-6. The stochastic distribution of the genetic risk factor expressed as the number of heritable defects per live-born Gy of population dose in the fetus.

4.6.4.3 The Risk Factor for Developmental and Reproductive Effects, R^{rep}_{HTO}

To estimate reproductive and developmental risk in humans from low-level HTO exposure, we use the model of Straume [1993] who has used ranges and distributions of gamma-ray-induced risks to construct a range of likely values for the dose-response function for HTO doses. From these data we developed a stochastic-dose response function for the number of reproductive and developmental effects expected per Gy of dose to the live-born infant. The probability density function of this model is shown in Figure 4-7. This distribution has respective median and mean values of 0.15 and 0.17 defects per live-born Gy of population dose. The range of this distribution is from 0 to 0.4, and the CV is approximately 0.45.

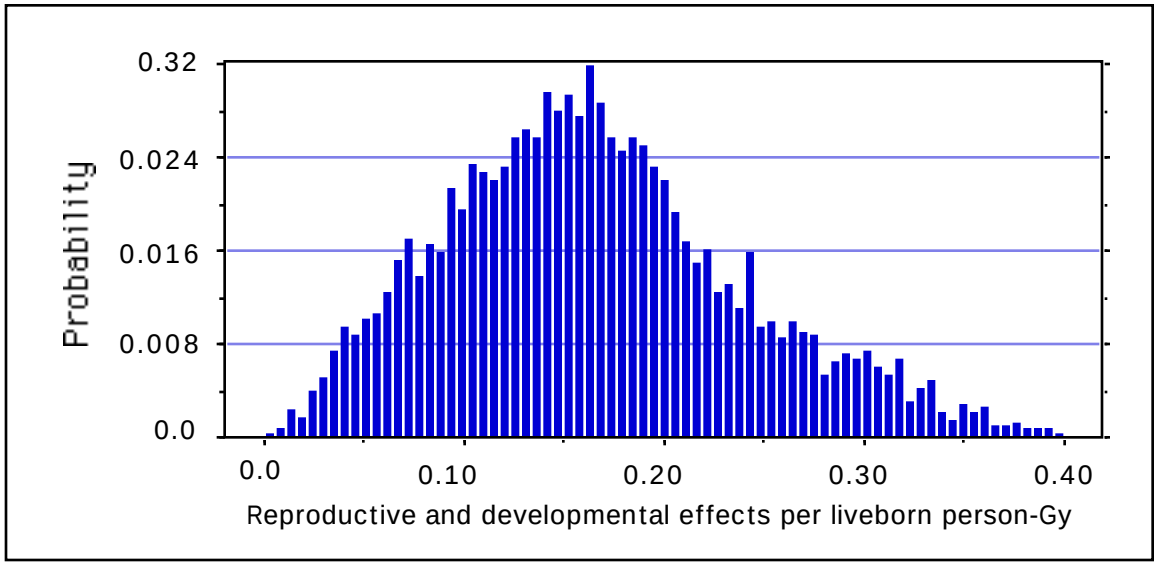


Figure 4-7. The distribution of reproductive and developmental effects associated with population doses of tritiated water expressed per average dose in Gy within that population. This model is based on recommendations of Straume [1993].

4.7 Estimated Health Risks for Tritium Releases from the NTLF

In this section, we quantify the potential health risks to the populations in and near the NTLF facility. The purpose of this assessment is to determine how tritium doses and potential health effects might be distributed among the occupational and nonoccupational populations of LBNL, the University of California (UC), and the cities of Berkeley and Oakland.

Three geographic zones and associated populations are defined in order to carry out this analysis (see Figure 4-8). Zone 1 includes the natural bowl that surrounds the NTLF facility and its tritium release stack. The population potentially at risk within this zone is the working population and its off-spring. Zone 2 includes the entire LBNL site; the UC property occupied by the Lawrence Hall of Science, the Samuel Silver Space Sciences Laboratory, the Mathematical Sciences Research Institute, and the Botanical Garden; and some single-family residences along the ridge above the LBNL site. Zone 3 includes the main UC Berkeley campus and areas of the city of Berkeley beyond Zone 2 and within 2 km of the NTLF.

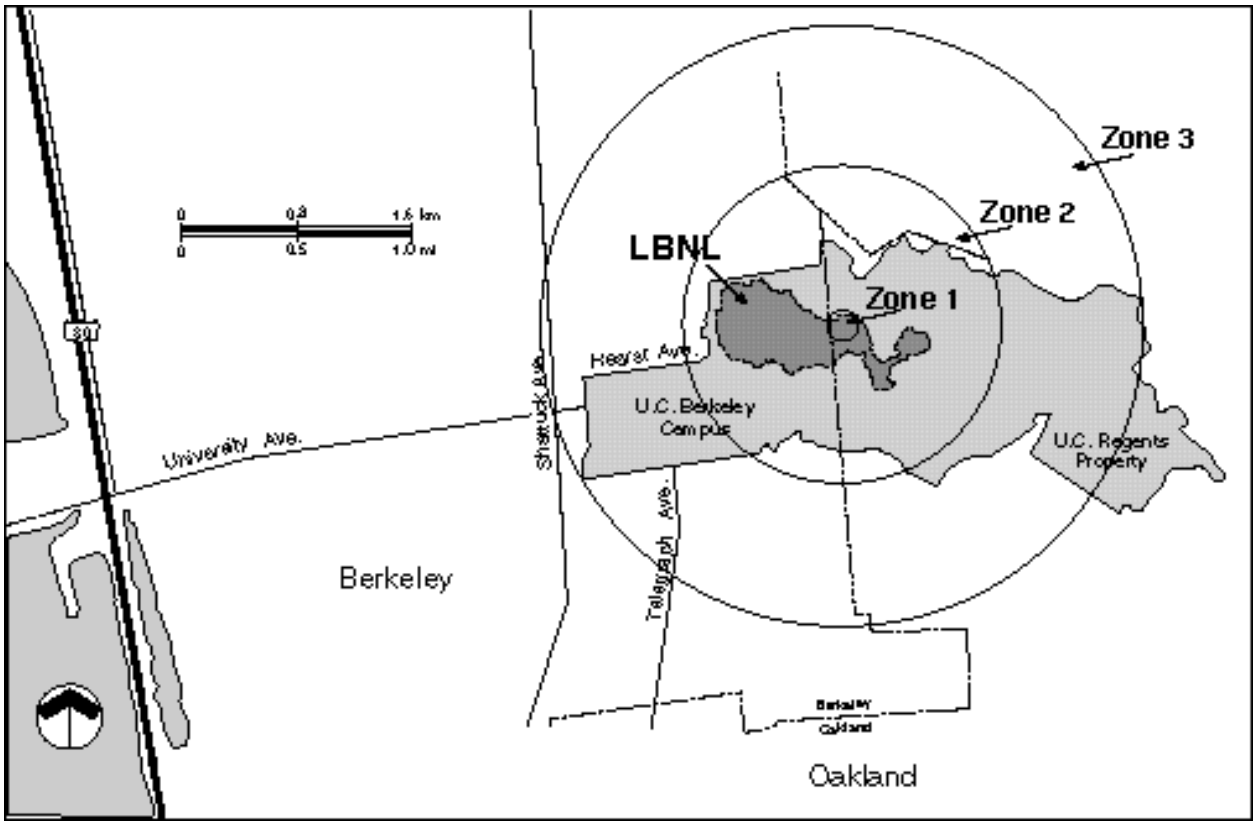


Figure 4-8. Geographical areas of tritium release, zones 1, 2, and 3.

4.7.1 Tritium Concentrations in Air, Water, and Soil of the NTLF Environment

The first step of our analysis is to characterize the concentrations of tritium in air, water, and soil of the proximate NTLF environment. The model reproduces the upper range of tritium concentrations that have been measured in the environment near the NTLF site. In air, tritium concentrations have been measured in the range of 10 to 100 Bq/m^3; in ground water and surface water runoff (hydraugers and streams) 40 to 800 Bq/L have been measured; and in rainwater 60 to 733 Bq/L have been observed [Schleimer and Pauer, 1991]. The reasonable upper bound tritium concentrations in each of the three exposure zones are estimated using the transport models described above and in Appendix A. These concentrations are compared to recently measured values in Appendix F.

Landscape, climate and hydrology parameters used in the analysis are derived from site-specific information. These parameters are summarized in Table 4-6. The references and methods used to obtain these values are described in detail in Appendix

C. The model used to determine tritium concentrations in Zones 1 and 2 is a site-specific model, which is described in Appendix A. It is based on the CalTOX model, which is a standard model used by the California Department of Toxic Substances Control for assessing risks at toxic substances release sites [McKone, 1993]. In Zone 3, we use the EPA radionuclide air dispersion model CAP88 to determine tritium concentration in air. As is discussed in Chapter 1 of this report, the site-specific model and the CAP88 model give close dose and risk estimates in Zone 2. The CAP88 model is not appropriate in Zone 1, because of the proximity to the source and because of the complex terrain. For application in Zone 3, we note that the CAP88 model calculates ingestion doses by pooling all vegetation within 80 km of the tritium source and assuming this vegetation provides some fraction of the food consumed by any individual in this area. Since this algorithm is not realistic, based on what is known about food distribution patterns in this area, we decided to use only the calculated air concentration from CAP88 in combination with the dose models developed for Zone 2 to estimate the exposure, dose and risk in Zone 3.

Table 4-6
Landscape properties for the NTLF Environment.

Parameter description	Symbol	Mean value	CV	Reference(s)
Yearly average wind speed, m/s	v_w	2	0.3	Thorson [1996]
Yearly average temperature, °C	*T*	12.5	0.2	Merry [1991] NOAA [1974]
Yearly average relative humidity, %	*RH*	79	0.04	Merry [1991] NOAA, [1974]
Soil compartment depth, m	d_s	2.5	0.5	Thibodeaux, [1994] Murphy [1993]
Volumetric moisture content of soil, L(water)/L(soil)	$\emptyset_s$	0.3	0.1	van der Leeden et al. [1991]
Annual average precipitation, m/y	*rain*	0.64	1.0	Merry [1991] NOAA [1974]
Annual average evapotranspiration, m/y	*evapotrans*	0.45	0.14	van der Leeden et al. [1991]
Annual average runoff, m/y	*runoff*	0.13	0.26	van der Leeden et al. [1991]
Infiltration to ground water, m/y	*recharge*	0.06	0.26	This report
Scavenging efficiency	Aq_{rain}	0.4	0.2	Murphy [1993]

4.7.1.1 Source Term

The NTLF currently releases tritium at a rate of approximately 100 Ci/y (3.7 trillion Bq/y). This has been typical since 1990. This value is lower than during the period 1982 to 1990, but higher than current releases by about a factor of 2 or more. According to the 1990 LBNL Site Environmental report, essentially all of LBNL's tritium emissions originate from the NTLF [LBNL Site Report, 1990]. The total inventory of tritium that is attached to the uranium beds (U-beds) is roughly 10,000 Ci—the U-beds are designed with a stoichiometric capacity for 25,000 Ci of tritium, and thus are always under-utilized. The release of the entire inventory, even in the case of an extreme event, is unlikely. It is even less likely that it would persist for an extended period (i.e., more than a few days). Note that a catastrophic accident would be a one-time release and certainly would not persist.

4.7.1.2 Source Area and Mixing Height of the Atmosphere Near the NTLF

The NTLF stack is located on the slope west of Building 75 (Figure 4-9). Its surrounding area is in a natural bowl or amphitheater. We used this bowl to characterize the initial mixing volume of the stack release. To be conservative, we used 15m as the mixing height for Zone 1, which may lead to an overestimate of the tritium concentration in air.

4.7.1.3 Predicted Concentrations in the Vicinity of the NTLF, Zone 1

The total volume of air for characterizing exposure in Zone 1 is estimated to be 471,000 m^3 and the volume of soil compartment in this zone is estimated to be 78,540 m^3. Based on these volumes, the landscape properties defined in Table 4-6, and the model equations in Appendix A, the estimated tritium turnover rates for the air and soil compartments in Zone 1 are shown in Table 4-7.

Table 4-7
Tritium Turnover Rates for the Air and Soil Compartments in Zone 1

Compartment	Turnover Rate	
Air	Turnover rate from air to soil, T_{as}	0.76 per day
	Turnover rate out of the air volume by wind, T_{ao}	224 per day
	Effective environmental residence of tritium in air, $1/L_a$	0.0044 day
Soil	Turnover rate from soil to air, T_{sa}	0.0016 per day
	Turnover rate out of the soil by leaching, T_{so}	0.0007 per day
	Effective environmental half-life of tritium in soil, $1/L_s$	400 days

Table 4-8 lists the air, soil, and runoff water concentrations of tritium predicted for Zone 1 based on these turnover rates used in Equations 4-5 and 4-6 under the assumption that there are continuous tritium releases of 100 Ci/y. The predicted concentrations are even below the regulatory standards for the ambient (i.e., nonoccupational) environment, 365 Bq/m3 in air and 740 Bq/L in water, as discussed in Section 4.6.3.

Table 4-8
Tritium Concentrations and Inventories in Zone 1,
Corresponding to a Release of 100 Ci/year

Compartment	Tritium concentration (Bq/m^3)	Tritium inventory (Bq)
Air	96	4.5×10^7
Soil	1.8×10^5	1.4×10^{10}
Runoff water	5.8×10^5 (580 Bq/L)	n/a

4.7.1.4 Predicted Concentrations in Zone 2

Zone 2 has a larger radius, and we used 25 m as the mixing height for estimating the tritium concentrations in Zone 2. With a radius of 1100m, the total volume of air for characterizing exposure in Zone 2 is estimated to be 9.5×10^7 m^3 and the volume of soil in this zone is estimated to be 9.5×10^6 m^3. Based on these volumes, the landscape properties defined in Table 4-6, and the model equations in Appendix A, we estimated the tritium turnover rates given in Table 4-9 for the air and soil compartments in Zone 2.

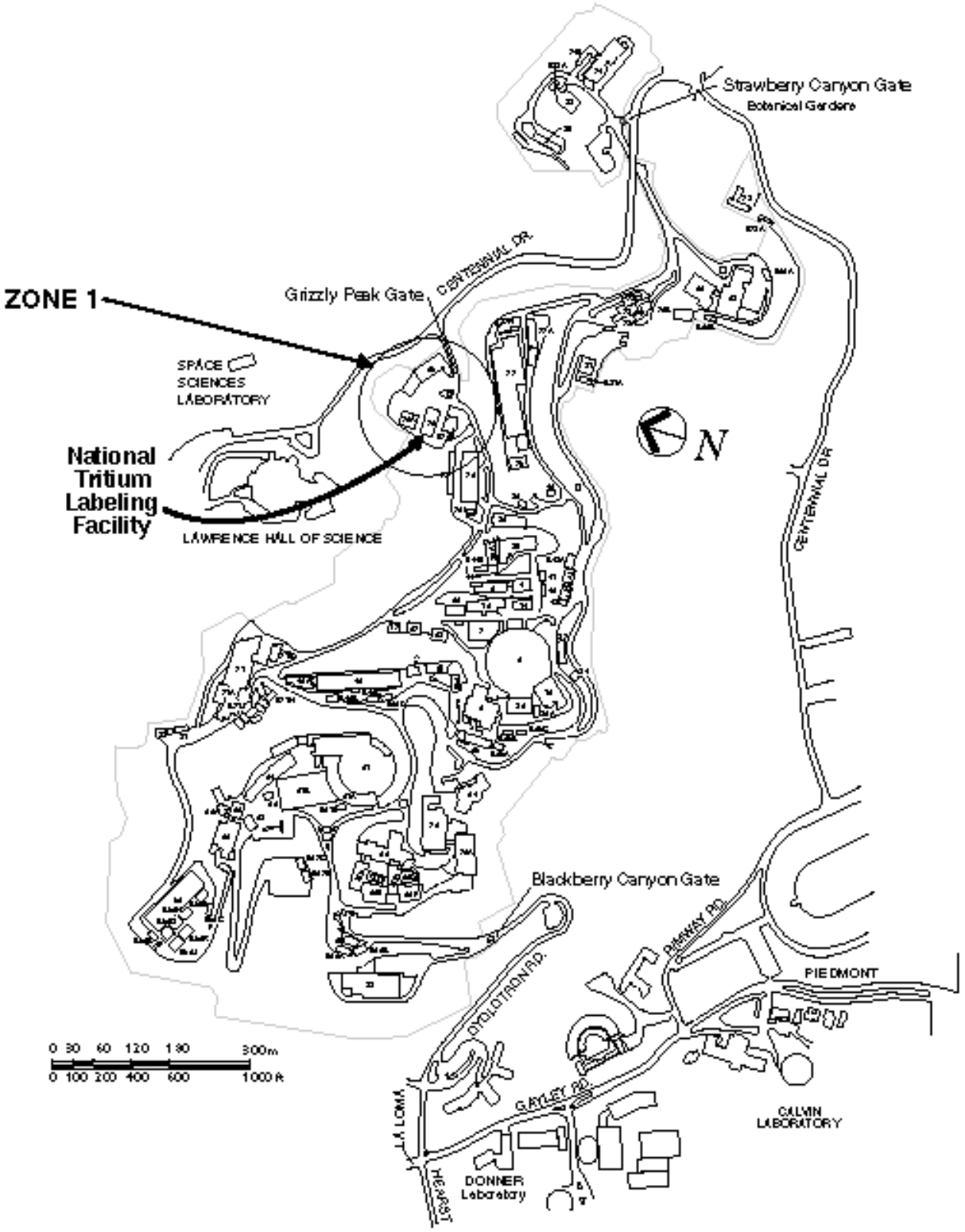


Figure 4-9. Location map. The NTLF is located in Building 75 on the LBNL site.

Table 4-9
Tritium Turnover Rates for the Air and Soil Compartments in Zone 2

Compartment	Turnover Rate	
Air	Turnover rate from air to soil, T_{as}	0.69 per day
	Turnover rate out of the air volume by wind, T_{ao}	20 per day
	Effective environmental residence of tritium in air, $1/L_a$	0.047 day
Soil	Turnover rate from soil to air, T_{sa}	0.0016 per day
	Turnover rate out of the soil by leaching, T_{so}	0.0007 per day
	Effective environmental half-life of tritium in soil, $1/L_s$	400 days

Table 4-10 lists the concentrations of tritium in air, soil, runoff water, vegetation HTO, and vegetation OBT predicted for Zone 2 using releases of 100 Ci/y. The HTO levels in vegetation were derived by assuming that vegetation water is a mix of 75% atmospheric water and 25% soil water [Murphy, 1993; Anspaugh et al., 1973]. The OBT levels in vegetation were derived by assuming that the OBT compartment contains about 3% of the hydrogen in fresh-plant material such as vegetables [Diabate and Strack, 1993]. We assume that the OBT level in fresh vegetables is 0.03 times HTO levels in plant water. For releases of 100 Ci/y the predicted concentrations are below the regulatory standards for the ambient (i.e., nonoccupational) environment, 365 Bq/m^3 in air and 740 Bq/L in water, as discussed in Section 4.6.3.

4.7.1.5 Predicted Concentrations in Zone 3

In Zone 3, air concentrations are obtained using CAP88 (see Appendix F) with an

Table 4-10
Tritium Concentrations and Inventories in Zone 2, Assuming a Release of 100 Ci/Year

Compartment	Tritium concentration, Bq/m^3	Tritium inventory, Bq
Air	5.2	4.9×10^8
Soil	1.5×10^4	1.4×10^{11}
Runoff water	4.8×10^4 (48 Bq/L)	n/a
Vegetation (HTO levels)	110 Bq/kg (fresh mass)	n/a
Vegetation (OBT levels)	3 Bq/kg (fresh mass)	n/a

adjustment to account for tritium added by the runoff in Strawberry Creek. Since Zone 3 represents the region from one to two kilometers from the NTLF and beyond, we use the highest 90° sector yearly average tritium concentration produced by CAP88 at a distance of 1.5 km from the NTLF. This sector is the northwest sector with an estimated annual concentration of $0.35\ Bq/m^3$ associated with a $100\ Ci/y$ release rate. This is where there is a rather high frequency of wind blowing from NTLF. As discussed below, we add to this concentration an amount used to account for evaporation of tritiated water from Strawberry Creek.

From measurements taken from air, rain water, soil, and surface water near the NTLF [Thorson, 1996], rain water appears to be washing tritium out of the air and into surface soil and the interstitial water of the soil . Some of the tritium in the soil water moves as runoff in the Chicken Creek Basin from which it is carried into Strawberry Creek and down toward the Berkeley Campus. This transfer by rainwater and runoff is used to assess tritium doses to those who come in contact with the lower portion of Strawberry Creek on the UC Berkeley Campus. This section illustrates how we estimated tritium concentrations in water and air associated with the segment of Strawberry Creek that flows through the Berkeley Campus.

Only a small fraction of the water flowing down Strawberry Creek (into Zone 3) originates from Zone 1 (bowl area). Assuming most of the stream flow stems from runoff, this fraction can be estimated as:

$$F_{S,bwl} = A_{bwl} / A_{S,Ctchmt} \tag{4-15}$$

where $F_{S,bwl}$ is the fraction of Strawberry Creek flow originating from the "bowl area," A_{bwl} is the area of the Zone 1 and $A_{S,Ctchmt}$ is the total area of the Strawberry-Creek catchment. This fraction is estimated to be roughly

$$F_{S,bwl} = 0.01 \tag{4-16}$$

Based on the fraction derived in Equation 4-16, we estimate that the tritium concentration in Strawberry Creek is on the order of 1% of the tritium water concentration in Zone 1. Based on the mass-balance model for water evaporation (Equation 4-17) in the area of the UC Campus, we estimate that evaporation from Strawberry Creek could contribute no more than about 0.01% to the total water inventory in air above the campus.

This analysis was carried out as follows. We assumed that the flow path of Strawberry Creek through the UC Berkeley campus and city is on the order of 2000 m (1.3 mile) and that it has an average width of 1 meter and depth of 0.5 meter. For evaporation of water from fast-moving water bodies, Southworth [1979] has shown that the rate of water evaporation is limited by the rate of mass transfer of saturated vapor in the air above the water. Furthermore, he has shown that this evaporation rate depends on the wind speed over the water, the water flow velocity, and the difference between the saturated

and average relative vapor concentrations in air. This evaporation rate is given as follows:

$$\textit{evaporation rate}\ (\mathrm{m/d}) = 0.00316 \times 86400\ \mathrm{s/d} \times (v_w + \textit{current}_w) \times [\varnothing_{a(100\%)} - \varnothing_a] \qquad (4\text{-}17)$$

where v_w is the yearly average wind speed (3 m/s from Table 4-6), $\textit{current}_w$ is the flow rate of the stream (1 m/s assumed), $\varnothing_a(100\%)$ is the volumetric water content of the air at saturation and $\varnothing_a$ is the volumetric water content of the air at the average relative humidity. Using Equations A-2 and A-3 in Appendix A with an assumed daytime temperature of 293 K and a yearly average daytime relative humidity of 70%, we obtain $\varnothing_a(100\%) = 1.7 \times 10^{-5}$, $\varnothing_a = 1.2 \times 10^{-5}$ and an evaporation rate of 0.005 m/d. Based on the stream dimensions already given, this amounts to a total mass evaporation of 10 m^3 per day into the surrounding volume. Based on the box model already described, assume the residence time of this air mass to be 0.02 day, then the water coming from Strawberry Creek is on the order of 10^{-6} of the water in this air volume. The uncertainty is estimated to be 5 times higher or lower, and most likely lower. Table 4-11 gives the estimated Zone 3 tritium inventories and concentrations in air and surface water.

Table 4-11
Tritium Concentrations and Inventories in Zone 3, Assuming a Release of 100 Ci/Y

Compartment	Tritium concentration, Bq/m^3	Tritium inventory, Bq
Air	0.35	n/a
Surface water (Strawberry Creek)	1.1×10^4 (11Bq/L)	n/a

4.7.2 Generic Calculations of Intake, Uptake, Body Burdens, and Dose

This section presents the mathematical expressions used to estimate the inhalation, dermal uptake, and ingestion exposures in each of the three zones.

4.7.2.1 Average Intake by Inhalation

The average intake of tritium in Bq/d per kg body weight by inhalation in a working population is calculated using the yearly average tritium concentration of the air in each zone, $C_{air}(Z_i)$ Bq/m^3; the working inhalation rate per unit body weight, BR_w m^3/kg-h; the exposure time at work, ET_w h/d; and the exposure frequency at work, EF_w days/y.

$$Intake(inh) = \frac{BR_w \times ET_w \times EF_w}{365 d/y} \times C_{air}(Z_i) \quad (\text{Bq/kg-d}) \tag{4-18}$$

The average intake of tritium in Bq/d per kg body weight by inhalation in a nonoccupational population is calculated using the yearly average tritium concentration of the air of each zone, $C_{air}(Z_i)$ Bq/m^3; the active and resting inhalation rates per unit body weight, BR_a and BR_r in m^3/kg-h; the exposure time at home, ET_h h/d; the exposure frequency at home, EF_h days/y; and the assumed resting time at home, 8 hours.

$$Intake(inh) = \frac{\left(BR_r \times 8 + BR_a \times ET_h\right) \times EF_h}{365 d/y} \times C_{air}(Z_i) \quad (\text{Bq/kg-d}) \tag{4-19}$$

Values used for the parameters in these expressions are discussed in Section 4.5 and Appendix B.

4.7.2.2 Average Dermal Uptake

The average uptake of tritium in Bq/d per kg body weight by dermal uptake in the working population is calculated using the yearly average tritium concentration of the air in each zone, $C_{air}(Z_i)$, in Bq/m^3; the surface area per unit body weight, SA_b, in m^2/kg; the exposure time at work, ET_w, in h/d; the exposure frequency at work, EF_w, in days/y; and the permeability for tritium in air through the skin, K_p^{air}, in m/h.

$$Uptake(drm) = \frac{SA_b \times ET_w \times EF_w}{365 d/y} \times K_p^{air} \times C_{air}(Z_i) \quad (\text{Bq/kg- d}) \tag{4-20}$$

Equation 4-20 was also used for non-occupational exposures to air by replacing ET_w and EF_w with the exposure time and exposure frequency at home, ET_h and EF_h. For recreational exposures to water, one needs to replace ET_w and EF_w with the exposure time and exposure frequency for recreation, ET_{sw} and EF_{sw}; replace the air permeability K_p^{air} with the water permeability K_p^{water}; and $C_{air}(Z_i)$ with $C_{water}(Z_i)$. Values used for the parameters in this expression are discussed in Section 4.5 and Appendix B.

4.7.2.3 Average Intake by Ingestion of Homegrown Foods

The average intake of tritium in Bq/d per kg body weight by ingestion of homegrown produce is calculated using the yearly average tritium concentration of the vegetation in each zone, $C_{veg}(Z_i)$ Bq/kg and the ingestion rates of exposed and unexposed produce, I_{ep} and I_{up} (in kg/kg-d).

$$Intake(ing) = (I_{ep} + I_{up}) \times C_{veg}(Z_i) \quad (\text{Bq/kg- d}) \tag{4-21}$$

Values used for the parameters in this expression are discussed in Section 4.5 and Appendix B.

4.7.2.4 Average Ingestion Intake of Surface Water During Recreation

The average intake of tritium in Bq/d per kg body weight by ingestion during water recreation is calculated using the yearly average tritium concentration in the water of Zone 3, $C_{water}(Z_i)$ (in Bq/m^3); the ingestion rate during the activity, I_{flr} (in L/kg-h); the exposure time and exposure frequency for recreation, ET_{sw} (in h/d) and EF_{sw} (in d/y); and a conversion factor from m^3 to L.

$$Intake(ing) = \frac{I_{flr} \times ET_{sw} \times EF_{sw}}{365 d/y} \times 10^{-3} m^3/L \times C_{water}(Z_i) \quad (\text{Bq/kg-d}) \qquad (4\text{-}22)$$

Values used for the parameters in this expression are discussed in Section 4.5 and Appendix B.

4.7.2.5 Total Body Burden of Tritiated Water

The total body burden in Bq/kg from all exposure routes for an average individual within the population is the sum of inhalation and ingestion intakes and dermal uptake in Bq/day multiplied by the removal time. The removal time is equal to the effective biological half-life, $T_{1/2}^{tlt}$, divided by 0.693.

$$Burden(adult) = \frac{[Intake(inh) + Intake(ing) + Uptake(drm)] \times T_{1/2}^{tlt}}{0.693} \quad (\text{Bq/kg}) \qquad (4\text{-}23)$$

As discussed above, $T_{1/2}^{tlt}$ is 15 days for HTO and 48 days for OBT.

4.7.2.6 Estimated Live-Born Infant Body Burden

The body burden of tritium in a fetus is assumed to be the same as the mother.

$$Burden(fetus) = Burden(adult) \qquad (4\text{-}24)$$

4.7.2.7 Potential Infant Intake and Body Burden through Breast Feeding

In estimating infant exposure through breast milk, the tritium concentration in breast milk is assumed to equal the tritium burden of the mother. The infant burden is then

equal to the breast-milk intake, I_{bm} in kg(milk) per kg body weight per day, times the removal time in the infant.

$$Burden(infant) = \frac{Burden(adult) \times I_{bm} \times T_{1/2}^{tlt}}{0.693} \quad (Bq/\ kg) \tag{4-25}$$

4.7.2.8 Total Dose, Population Risk, and Individual Risk

The total dose in Gy associated with ingestion, inhalation, and dermal uptake is calculated from the product of body burden and a conversion factor (Equation 4-27) that translates from Bq / kg to Gy / y, as given by Equation 4-14.

$$Dose[Gy\ /\ y] = Burden[Bq\ /\ kg] \times 2.86 \times 10^{-8}[Gy\ /\ y\ per\ Bq\ /\ kg] \tag{4-26}$$

$$Factor = 2.86 \times 10^{-8}[Gy\ \ kg\ /\ y\ /\ Bq] \tag{4-27}$$

The population risk for cancer represents the estimated increase of fatal cancers per year due to exposures including adults and infants. The magnitude of the population for cancer risk depends on the number of exposed adults and the number of infants born to exposed adults.

$$\begin{aligned} &Population\ Risk\ (cancer)\ \ [cancers\ per\ year\ ] \\ &= [\ \text{Dose (adult)} \times N_{adults}(Z_i) + \text{Dose (infant)} \times N'_{infants}(Z_i) \times 2\ ] \times R_{HTO}^{can} \end{aligned} \tag{4-28}$$

where $N_{adults}(Z_i)$ is the total number of adults in the population, $N'_{infants}(Z_i)$ is the number of infants born per year to adults in this population, and 2 years is the time that an infant is assumed to be breast fed. The individual lifetime cancer risk for an average individual is estimated as the product of the population risk and the exposure duration divided by the number of adults in the population.

$$Individual\ Lifetime\ Risk\ (cancer) = Dose\ (adult) \times ED \times R_{HTO}^{can} \tag{4-29}$$

The population risk for genetic effects represents the estimated increased hereditary effects per year per live-born child within the exposed population. The magnitude of the population risk for heritable defects depends on the total number of live births and the exposure to the parents of a child.

$$\begin{aligned} &Population\ Risk(genetic)[genetic\ effects\ per\ year] \\ &= Dose(adult) \times N'_{infants}(Z_i) \times R_{HTO}^{gen} \end{aligned} \tag{4-30}$$

Assuming one birth per adult per lifetime, we obtain

$$\begin{aligned} &\textit{Individual Lifetime Risk}\ (\textit{genetic})\ [\textit{genetic effects per lifetime}] \\ &= \textit{Dose}(\textit{adult}) \times R_{HTO}^{gen} \end{aligned} \tag{4-31}$$

The population risk for reproductive and developmental effects represents the expected number of effects per year per live-born child within the exposed population. The magnitude of the population risk for reproductive and developmental effects depends on the total number of live births and the dose to the fetus during development.

$$\begin{aligned} &\textit{PopulationRisk}(\textit{rep}-\textit{dev})[\textit{effects per year}] \\ &= \textit{Dose}(\textit{adult}) \times N'_{\textit{infants}} \left(\frac{Z_i}{\phi}\right) \times R_{HTO}^{rep} \end{aligned} \tag{4-32}$$

$$\begin{aligned} &\textit{Individual Lifetime Risk}(\textit{rep}-\textit{dev})[\textit{effects per live birth}] \\ &= \textit{Dose}(\textit{adult}) \times R_{HTO}^{rep} \end{aligned} \tag{4-33}$$

4.7.3 Estimated Doses and Risks in Zone 1

The population at risk is taken to include the working population in this zone as well as the infants born to mothers who are part of this working population. We assume that the number of adults in this population $N_{adults}(Z_1)$ is 200. We estimated the number of live-born infants per year associated with this population, $N'_{infants}(Z_1)$, by assuming that half of the working population are women and that each woman bears 2 children over a twenty year period.

$$N_{adults}(Z_1) = 200 \tag{4-34}$$

$$N'_{infants}(Z_1) = \frac{N_{adults}(Z_1)}{2} \times \frac{2\ infants}{20\ years} = 10\ infants/y \tag{4-35}$$

For the purposes of calculating lifetime individual risk, the exposure duration was assumed to be a working lifetime of 40 years. We estimated population risk and individual risks based on the equations in Section 4.7.2 for calculating intake, uptake, body burdens, dose, and risk, and on the tritium concentrations given in Section 4.7.1. The results for assumed releases of 100 Ci/y are in Table 4-12.

Table 4-12.
Predicted Doses and Risks for Zone 1, with a Release Rate of 100 Ci / year.

Dose Group	Total Dose[a] (Gy/year)	Relative Dose Fractions (Inhalation/Ingestion/Dermal)
Adult	1.4×10^{-5}	0.82/0/0.18
Nursing infant	3.2×10^{-5}	0/1/0
Live-born infant	1.0×10^{-5}	
Health End Point	**Population Risk per Year** (expected effects per year)	**Individual Risk per Lifetime** (probability in a lifetime)
Fatal Cancer	3×10^{-4}	5×10^{-5}
Cancer incidence [b]	4×10^{-4}	6×10^{-5}
Genetic defects	9×10^{-7}	9×10^{-8}
Developmental and reproductive effects	2×10^{-5}	2×10^{-6}

Notes to Table 4-12:

(a) Doses and corresponding risks are about nine times higher than doses measured by urinalysis in Zone 1 workers in 1995. This suggests that some assumptions about exposure were overly conservative.

(b) In this study we develop risk factors for cancer mortality; to estimate cancer incidence from cancer mortality, we use the ratio 6/5, which is the incidence/mortality ratio recommended by the ICRP (1991).

4.7.4 Estimated Doses and Risks in Zone 2

The population at risk in Zone 2 is taken to include the working population in this zone as well as the infants born to mothers who are part of this working population. The working population is assumed to be 6,000. In addition, the population is assumed to include some 4,000 residents who occupy the single-family homes near the LBNL site. All of these residents are assumed to consume food from home gardens. For purposes of assessing tritium metabolism and dose, children over the age of two are represented as adults. We assume that half of the population are women and that each woman bears 2 children over a twenty-year period. Thus, we have

$$N_{adults}(Z_2) = 6{,}000\ working\ adults + 4{,}000\ residents = 10{,}000\ individuals \quad (4\text{-}36)$$

$$N'_{infants}(Z_2) = N_{adults}(Z_2) / 20\ \text{years} = 500\ infants / y \quad (4\text{-}37)$$

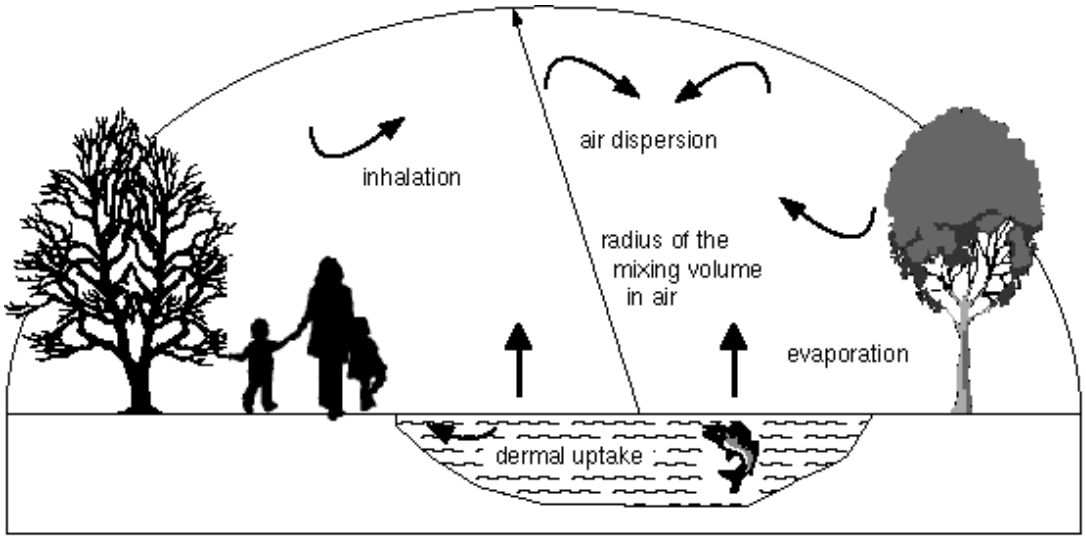
For the purposes of calculating lifetime individual risk, we only report the risk to the residential population, whose individual risk is about twice that of the occupational population. The exposure duration for the residential population is assumed to be 70 years. We estimated the population and individual risks based on the equations in Section 4.7.2 for calculating intake, uptake, body burdens, dose, and risk based on the tritium concentrations listed in Section 4.7.1. The results are listed in Table 4-13.

Table 4-13
Predicted doses and risks for Zone 2, with a release rate of 100 Ci / year.

Dose Group	Total Dose (Gy/year)	Relative Dose Fractions (Inhalation/Ingestion/Dermal)
Working Population		
Adult	7.3×10^{-7}	0.82/0/0.18
Nursing infant	1.7×10^{-6}	0/1/0
Live-born infant	5.4×10^{-7}	
Residential Population		
Adult	8.0×10^{-7}	0.53/0.15/0.32
Nursing infant	2.8×10^{-6}	0.19/0.69/0.12
Live-born infant	6.0×10^{-7}	
Health end point	**Population Risk per Year** (expected effects per year)	**Individual Risk per Lifetime** (probability in a lifetime)
Fatal Cancer	9×10^{-4}	5×10^{-6}
Cancer incidence	1×10^{-3}	6×10^{-6}
Genetic defects	3×10^{-6}	5×10^{-9}
Developmental and reproductive effects	6×10^{-5}	1×10^{-7}

4.7.5 Estimated Doses and Risks in Zone 3

We consider inhalation, ingestion, dermal uptake from air and surface water as potential exposures in Zone 3, as illustrated in Figure 4-10 and discussed in Section 4.7.1.5. For purposes of assessing tritium metabolism and dose, children over the age of 2 are represented as adults. We assume that the total number of individuals in this population, $N_{adults}(Z_3)$, is on the order of 100,000. We assume that half of the population are women and that each woman bears 2 children over a twenty-year period.



XBD 9505-01896.EPS

Figure 4-10. Exposure scenarios near Strawberry Creek. This diagram illustrates dermal uptake from water as a result of wading in the creek and inhalation and dermal uptake of tritium from the air envelope surrounding the creek, which contains elevated levels of tritium as a result of tritium in the creek.

$$N_{adults}(Z_3) = 100{,}000 \tag{4-38}$$

$$N'_{infants}(Z_3) = \frac{N_{adults}(Z_3)}{2} \times \frac{2\ infants}{20\ years} = 5{,}000\ infants/y \tag{4-39}$$

For the purposes of calculating lifetime individual risk, the exposure duration is assumed to be 70 years. We estimated the population and individual risks based on the equations in Section 4.7.2 for estimating intake, uptake, body burdens, dose, and risk, and based on the tritium concentrations listed in Section 4.7.1. Table 4-14 gives the results for assumed releases of 100 Ci/y.

Table 4-14
Predicted Doses and Risks for Zone 3, with a Release Rate of 100 Ci / year.

Dose Group	**Total Dose, Gy/year**	**Relative Dose Fractions** (Inhalation/Ingestion/Dermal)
Adult	1.2×10^{-7}	0.64/0.07/0.29
Nursing infant	4.0×10^{-7}	0.17/0.72/0.11
Live-born infant	0.9×10^{-7}	
Health end point	**Population risk per year** (expected effects per year)	**Individual risk per lifetime** (probability in a lifetime)
Fatal Cancer	1×10^{-3}	7×10^{-7}
Cancer incidence	2×10^{-3}	9×10^{-7}
Genetic defects	4×10^{-6}	8×10^{-10}
Developmental and reproductive effects	1×10^{-4}	2×10^{-8}

4.7.6 Step-by-Step Calculations

Table 4-15 provides a step-by-step summary of the exposure and risk assessment calculations. It provides a summary of how the environmental concentrations converts to human exposure, dose, and risk. The table also includes cross references to sections, equations to make the transition from one stage of the calculation to the next.

Table 4-15

A Step-By-Step Summary Of The Exposure And Risk Assessment Calculations

	Zone 1	**Zone 2**	**Zone 3**
Air concentrations Bq/m^3 [values in brackets are concentration in atmospheric water, Bq/L]	**96**	**5.2 [130]**	**0.35 [8.7]**
relevant equations	4-6	4-6	CAP88, 4-17
reference sections	4.4.1, 4.4.2 & 4.7.1.3	4.4.1, 4.4.2 & 4.7.1.4	4.7.1.5, Appendix E
Soil water Bq/L		**48**	**2**
relevant equations		4-5	4-5, 4-15, 4-16
reference sections		4.4.1, 4.4.2 & 4.7.1.4	4.7.1.5
Vegetation (free water) Bq/L		**110**	**7**
reference sections		4.7.1.4	4.7.1.4
Vegetation (OBT) Bq/kg		**3**	**0.2**
reference sections		4.7.1.4	4.7.1.4
Surface water Bq/L			**11**
relevant equations			4-15, 4-16
reference sections			4.7.1.5
Inhalation intake, Bq/kg/d	**18**	**1.0** (workers) **0.7** (residents)	**0.12**
relevant equations	4-18	4-18 & 4-19	4-19
reference sections	4.7.2.1	4.7.2.1	4.7.2.1
Dermal intake, Bq/kg/d	**3.9**	**0.2** (workers) **0.4** (residents)	**0.0546** (air) **0.0007** (water)
relevant equations	4-20	4-20	4-20
reference sections	4.7.2.2	4.7.2.2	4.7.2.2
Ingestion intake, Bq/kg/d	none	**0.19** (residents)	**0.01**
relevant equations	--	4-21	4-21 & 4-22
reference sections	--	4.7.2.3	4.7.2.3 & 4.7.2.4
Body water levels, Bq/L	**468**	**28** (residents)	**4.2**
relevant equations	4-23	4-23	4-23
reference sections	4.7.2.5	4.7.2.5	4.7.2.5
Annual dose rate, Gy/y	**1.3×10^{-5}**	**8.0×10^{-7}** (residents)	**1.2×10^{-7}**
relevant equations	4-26	4-26	4-26
reference sections	4.7.2.8	4.7.2.8	4.7.2.8
Individual risk per lifetime	**5×10^{-5}**	**5×10^{-6}** (residents)	**7×10^{-7}**
relevant equations	4-29	4-29	4-29

reference sections	4.7.2.8	4.7.2.8	4.7.2.8

4.8 Summary and Discussion

The estimated risks for tritium releases from the NTLF are quite low relative to the background incidence of the diseases considered—cancer, heritable genetic defects, and reproductive and developmental effects. The estimated cancer risk of the NTLF facility is orders of magnitude lower than the cancer incidence attributable to background radiation. Within Zone 3, the projected levels of tritium in the environment and the estimated population risk are so low that neither the levels of tritium present nor the potential health impacts could be easily detected by measuring devices or health surveys.

The highest estimated additional annual population cancer risk in Zone 1 is on the order of two cases per million population per year. This means that, if the facility continued to operate for a very long period of time with 200 people, we would have to wait on average about 2,500 years before we would see an additional cancer in this facility. In Zones 2 and 3, the population risks are slightly higher but the sample population is much larger so that the risk per individual is much lower.

An uncertainty analysis was given to assess the reliability of these results. The uncertainty analysis was based on a tiered approach that included the following steps:

1. Variance in the input values was clearly stated. At a minimum, this is done by listing the estimation error or the experimental variance associated with the parameters when these values or their estimation equations are listed in tables. Summary and justification of the assumptions used for each aspect of the model are provided. In addition, it is stated whether these assumptions are likely to result in representative values or conservative (upper bound) estimates of risk.
2. A sensitivity analysis was used to assess how model predictions are impacted by model reliability and data precision.
3. Variance propagation methods (Monte-Carlo methods) were used to map how the overall precision of risk estimates is tied to uncertainty associated with the model inputs.

Based on the range of parameter values used as input for the predictions of risk, we assessed the precision of the model predictions by making thousands of repeated calculations of risk with all input values varied within their likely ranges. For the estimations of cancer risk in Zone 1, we found that 50% of the range of output values were within a factor of 2 of the reported risk and 95% of the output values were within a factor of 10 of the reported risk.